SPECIFICATION

TITLE: A SYSTEM AND METHOD FOR INCREASING CHANNEL CAPACITY OF FIBER-OPTIC COMMUNICATION NETWORKS

Priority of PCT/US01/21062 filed June 29, 2001 and United States Provisional Application Serial No. 60/217,136 filed July 10, 2000 are hereby claimed.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to optical communication networks and more particularly relates to a system and method for increasing the channel capacity and total system throughput of a fiber-optic communication network utilizing three-dimensional spatial field.

2. Background Information

As data communication systems and networks consume more and more bandwidth, fiber-optics has emerged as a leading technology for metropolitan and long-haul data transmissions. Access techniques, adapted from electronics communication, such as Code Division Multiplexing (CDM), Frequency Division Multiplexing (FDM), and Time Division Multiplexing (TDM) have been used in fiber-optic systems and networks. For example, Wavelength Division Multiplexing (WDM) is essentially FDM in the optical domain. To further conserve the bandwidth of an optical

network, a so-called Dense WDM (DWDM) standard has been proposed with the channel separation set at 0.8 nm in wavelength, or 100 GHz in frequency.

One area unique to optical communications has provided another dimension for capacity enhancement. This is the polarization of an optical signal. Lithium Niobate (LiNbO) phase modulators and polarization controllers, and Pockels cells have been used to implement polarization shift keying (POLSK). Other investigations have considered polarization of signals in different wavelength channels. One example is in U.S. Patent No. 6,038,357 of Pan issued March 14, 2000 that discloses a fiber-optic PDM/WDM system comprising a plurality of sets of laser sources maintained at fixed polarization states. Each state represents a different channel. The design disclosed in that patent accomplishes an increase in the number of channels at the expense of using multiple sets of laser sources. Another U.S. Patent No. 6,025,944 of Mendez et al issued February 15, 2000 discloses a clever but complex coding scheme to perform hybrid mixing of Wave Division Multiplexing (WDM) and Code Division Multiple Access (CDMA). The tradeoff in using a complex switching and coding method to improve channel capacity is unclear.

It is one object of the present invention to provide a

system and method for increasing channel capacity and throughput of an optical communications network by a combination of Polarization Modulation (PM), Wavelength Division Multiplexing (WDM), and Time Division Multiplexing (TDM). Time division multiplexing increases the number of available channels while polarization modulation increases the throughput.

It is another object of the present invention to provide a system and method for increasing channel capacity and throughput by applying space-time modulation to guided optical communications.

Yet another object of the present invention is to provide a system and method of increasing channel capacity and throughput by direct modulation of optical sources.

Still another object of the present invention is to provide a system and method for increasing transmission distance by including signal amplification with optical amplifiers inserted in the optical transmission fiber.

Yet another object of the present invention is to provide a system and method for increasing channel capacity and throughput in which an optical wavelength cross-connect is inserted in an optical fiber transmission line to reuse wavelengths.

Still another object of the present invention for increasing channel capacity of an optical network in which

temporal data streams from time division multiplexers are modulated on optical sources.

Still another object of the present invention is for increasing throughput of an optical network in which spatial data streams from time division multiplexers are modulated on outputs of optical sources by varying the polarization states of the optical field.

Yet another object of the present invention is to provide a system and method for increasing channel capacity and throughput which can be applied to conventional wavelength division multiplexing ring network.

Yet another object of the present invention is to provide a system and method for increasing channel capacity and throughput which can be applied to a conventional wavelength division multiplexing fiber-optic star coupled network of a plurality of wavelengths.

Still another object of the present invention is to provide a system and method for increasing channel capacity and throughput by application to a conventional wavelength division multiplexing fiber-optic data bus network operating with multiple wavelengths comprised of multiple Network Interface Units (NUI) communicating over an optical fiber network.

<u>BRIEF DESCRIPTION OF THE INVENTION</u>

The purpose of the present invention is to apply space-time modulation to increase channel capacity of optical communication networks by utilizing a three-dimensional spatial field.

The basis of the present invention disclosed herein is a direct application of the space-time modulation to guided optical communications, where a single mode fiber can be used for long-haul data transmission. The space-time modulation provides capacity expansion by utilizing the three-dimensional spatial field. The spatial modulation can be compressed in the form of spatial carriers, Ex, Ey. The relationship of the x y components and its propagation direction z forms the basis functions for data transmission.

When the spatial dimension is not being used as in the case of a linearly polarized signal, all data loading is limited in time along the propagation axis. Assuming a space-time separable channel, the temporal information carrier on the propagation axis becomes independent of the transverse plane where the relative phase position (state of polarization) can be modulated. By utilizing both spatial and temporal modulation, total system throughput can be substantially increased.

In the present invention, a combination of Polarization Modulation (PM), Wavelength Division Multiplexing (WDM), and Time Division Multiplexing (TDM) technology is utilized. The

hardware implementation of the three-dimensional spatial field processing is simple and straight forward. Due to the special design disclosed herein, the polarization, wavelength, and time channels enjoy total independent operation from each other. The resulting degrees of freedom add flexibility in supporting multiple users in a large variety of optical network configurations and services. Furthermore, the independent operations imply more data channels can be added as the fiber-optic network grows under market demand. Thus, once the optical fibers are laid; only incremental cost is required to cover a fixed size network. The overall channel capacity in terms of number of channels as well as data rate throughput is simply the product of the contribution from individual modulation and multiplex technology. This aggregate throughput can be orders of magnitude higher than each multiplex technology itself.

In the system and method of the present invention using the combination of PM, WDM, and TDM technology, the TDM increases the number of available channels while the PM increases the throughput. In accordance with the present invention, the channel capacity of conventional wavelength division multiplexing network system can be significantly increased depending on the levels of polarization modulation. For a

typical WDM system using N signal sources transmitting to N receivers at N different wavelengths, only N communication channels are available for data transmission. The present invention effectively increases N by a factor equal to the time division multiplexing channels. This is achieved without requiring additional sets of optical or laser sources.

In one embodiment of the present invention, the system has direct modulation of optical sources. The system has a plurality of optical network sources each driven by a temporal path consisting of time division data from a transmitter data processor. The transmitter data processor multiplexes a plurality of input channels of data into a time division multiplex data stream of temporal and spatial data. Spatial data output of the transmitter data processor is directed to a polarization modulator while temporal data is sent to the optical source for direct modulation. Each optical source input is connected to a transmitter data processor and its output to a polarization modulator. The polarization modulator produces optical symbols corresponding to various polarization states.

Each polarization modulator output is sent to a Wavelength Division Multiplexer (WDM) before being transmitted through an optical fiber. The optical fiber is connected to a wavelength division demultiplexer. Each wavelength output of the

demultiplexer is connected to a polarization demodulator followed by direct photo-detection and then a receiver data processing circuit. The receiver data processor demultiplexes the received time division multiplex data from the received spatial and temporal data channels into a plurality of output data channels.

A variation of the invention includes signal amplification with optical amplifiers inserted in the single optical transmission fiber. The use of signal amplification in the optical fiber extend the transmission distance of the optical fiber for long haul applications.

Another optional but preferred feature of the invention is the use of an optical wavelength cross-connect inserted in the optical fiber transmission line to reuse these wavelengths a plurality of times for connecting various transmitters and receivers rather than having wavelength routing without reuse. In this embodiment, a first user can use a particular wavelength to establish a link with a second user while simultaneously a subsequent user can reuse the same wavelength and channel to communicate with yet another user. Compared to a typical wavelength division multiplexed fiber-optic network system operated with a pre-determined number of wavelengths without reuse, the total number of channels with this new design is

substantially increased.

Another object of the present invention is a system in which the optical source or sources are not directly modulated. Rather, the optical output signal from the source or sources is spatially modulated in polarization and temporally modulated in amplitude, phase, and/or frequency by a polarization modulator performing the function of space-time modulation. The polarization modulator is driven by a transmitter data processor. In most applications, indirect amplitude or indirect phase modulation is desirable to preserve the stability of the optical source. The output of each polarization modulator is sent to a wavelength division multiplexer before being transmitted over an optical fiber. The optical fiber terminates at a WDM demultiplexer. Each wavelength is then demodulated by a polarization demodulator followed by coherent detection and finally processed in a received data processor. The coherent optical detection can be implemented with a local optical source using homodyne or heterodyne demodulation techniques.

The method and system of the present invention can also be applied to a conventional wavelength division multiplexing ring network. In this embodiment each source is directly modulated by a transmitter data processor. The output temporal path of each transmitter data processor is directed to an optical source

while spatial data is sent to a polarization modulator that produces optical symbols corresponding to various polarization states as before.

The output of each polarization modulator is then multiplexed by a wavelength division multiplexer before transmission over an optical fiber to add/drop nodes in the ring network. Each add/drop node of multiple add/drop nodes around the ring operates at a specific wavelength providing multiple time division multiplexing channels. The specific wavelength output of the add/drop node of the ring network is then connected to a polarization demodulator. This demodulation process is followed by feeding the signals to direct photo-detection and receiver data processing. The receiver data processor demultiplexes the received TDM data from the received spatial and temporal data channels into a plurality of output data channels.

Each add/drop node of the multiple nodes in the ring network includes a receiver/transmitter pair. The receiver is capable of polarization demodulation, direct photo-detection and received data processing of multiple time multiplexed output channels. Transmitter reverses the operation by time multiplexing of data channels, direct modulation onto the optical source followed by polarization modulation.

A wavelength division demultiplexer extracts a signal at one wavelength and transmits the signal back at the same wavelength. The same operation is repeated in the next or sequential add/drop nodes of the optical fiber until it reaches the end of the ring. Access into and egress out of the ring network is under computer control. If any receiver/transmitter processor wishes to transmit signals, its transmitter sends data through the time division multiplexed channel. These optical signals pass through the WDM multiplexers and circulate around the ring. Hence, in this embodiment, the number of network users at each add/drop nodes increases by a substantial factor.

Another application of the system is in a conventional WDM fiber-optic star network of a plurality of wavelengths that consist of a star coupler connected to a plurality of nodes. Each node transmits at one of the optical wavelengths equal to the number of nodes to the star coupler which distributes the optical signals. One of the plurality of nodes is used as a central office for access and egress control of the network. The star coupler broadcasts any optical signals from one node to all the other nodes in the network. Each node also each receives and demultiplexes broadcasts signals from star coupler to determine whether it has messages sent from other nodes.

Another embodiment of the present invention is adapted to a

star network. Each star network has now increased its throughput by M times, while the total number of channels has gone up to NxL times. Nodes are connected by a star coupler. Network users in the present invention at each node are allocated specific TDM channels in the transmitter/receiver data processor. The temporal data path is directed to the optical source while the spatial data is sent to the polarization modulator. The modulator produces symbols corresponding to various polarization states. The output of each polarization modulator at the particular wavelength is sent to the star coupler for distribution of the wavelength multiplexed signal to all other nodes. On the return path, the WDM signal is extracted from a WDM demultiplexer and polarization demodulated. This is followed by a photo-detector and transmitter/receiver data processor. The processor demultiplexes the received TDM data and the received spatial data.

The system disclosed herein can also be applied to conventional WDM fiber-optical data bus network operating with multiple wavelengths comprised of multiple Network Interface Units (NIU) communicating over an optical fiber. In the conventional WDM fiber-optic data bus network, each network interface unit, by which a user communicates over the network, has multiple fixed wavelength optical transmitters and multiple

receivers. Due to hardware cost of installing multiple pairs of transmitter/receivers for network interface unit, each NIU generally only contains a few pairs of transmitter/receivers such that multiple hops are required to relay messages from one user to another within the network. Because of this reason, network loading becomes a problem during high network utilization period. Furthermore, each NIU can only be shared by a small limited number of users due to few pairs of transmitter/receivers are available.

In another optional embodiment of the present invention, each fixed wavelength transmitter at the NIU is driven by a transmitter data processor. The temporal data path from the transmitter data processor is directed to the optical source while the spatial data is sent to a polarization modulator that produces symbols corresponding to various polarization states. The output of each polarization modulator at specific wavelengths circulates in the data bus. Reverse operations are carried out by a receiver. An optical signal at each wavelength is connected to a polarization demodulator. This is followed by direct photo-detection and receiver data processing. The processor demultiplexes the received TDM data and its received spatial data. With a plurality of additional TDM channels, the same data processor can now support a number of users equal to

the number of additional channels without installing more transmitter/receiver pairs.

In the present invention when increasing channel capacity and throughput of an optical communication network, a combination of polarization modulation, wavelength division multiplexing, and time division multiplexing technology is utilized. Time division multiplexing increases the number of available channels while polarization modulation increases the throughput. A systems theory related to the present invention is described by Victor Lo in "*On A Statistical Space-Time Modulation Theory*," Proc. IEEE P.R. Conference on Communications, Computers and Signal Processing, pp. 584-589, Victoria, B.C., Canada, June, 1989. Hardware implementation of a polarization modulator has been described by Sergio Benedetto in "*Multilevel Polarization Modulation Using A Specifically Designed LiNbO,*", IEEE Photonic Tech. Lett, August 1994, pp. 949-951. Details of a polarization demodulator suitable for the invention are discussed in "*Multilevel Polarization Shift Keying: Optimum Receiver Structure and Performance Evaluation*," IEEE Trans. on Comm., March 1994, and demodulation tracking loop in "*Polarization Recovery In Optical Polarization Shift-Keying Systems*" IEEE Trans. on Comm., vol. 45, no. 10, October 1997.

Due to the unique design disclosed in this application,

polarization, wavelength, and time channels enjoy total independent operation from each other. The increase in the degrees of freedom from this design adds flexibility in supporting multiple users in a large variety of optical network configurations and services. Furthermore, the independent operations imply more data channels can be added as the fiber-optic network grows under market demand. Thus, once the optical fibers are laid; only incremental costs is required to cover a fixed size network. The overall channel capacity in terms of number of channels as well as data rate throughput is simply the product of contribution from individual modulation and multiplex technology. This aggregate throughput can be orders of magnitude higher than each technology itself.

The above and other objects, advantages, and novel features of the invention will be more fully understood from the following detailed description and the accompanying drawings, in which:

<u>BRIEF DESCRIPTION OF THE DRAWINGS</u>

Figure 1A is a schematic block diagram of one embodiment of a system for increasing channel capacity and throughput of optical communication networks.

Figure 1B is a schematic block diagram of the embodiment of one with the addition of signal amplification in the optical

transmission line.

Figure 1C is a schematic block diagram with a variation of the embodiment illustrated in Figure 1 utilizing an optical wavelength cross-connect for reusing wavelengths.

Figure 2A is a schematic block diagram of a variation of the invention illustrated in the first embodiment of Figure 1 in which optical sources are not directly modulated.

Figure 2B is a variation of the system illustrating in Figure 2A in which signal amplification is inserted in the optical transmission line.

Figure 2C is another variation of the system of Figure 2A including an optical wavelength cross-connect to reuse wavelengths.

Figure 3 is a schematic diagram illustrating a configuration of an optical wavelength cross-connect for insertion in a fiber transmission line to reuse wavelengths multiple times.

Figure 4A is a schematic block diagram of a transmitter data processor that essentially performs the switching function of a typical time division multiplexer.

Figure 4B is a schematic block diagram of a receiver data processor that demultiplexes input TDM data streams from the spatial and temporal channels into multiple output data

channels.

Figure 5A is a diagram illustrating the mapping operation of a M-level polarization modulator from digital data to polarization symbols in the Poincare sphere using Stokes parameters.

Figure 5B is a block diagram illustrating the implementation of the mapping operation of Figure 5A.

Figure 5C is a schematic block diagram illustrating a demodulator comprised of a Stokes parameters estimator, a control loop to track changes in polarization state and a decision logic block.

Figure 6 is a schematic block diagram according to the invention applied to a ring network having multiple add/drop nodes.

Figure 7 is a schematic block diagram according to the invention with the system being applied to a WDM fiber-optic star network of a plurality of wavelengths.

Figure 8 is a schematic block diagram illustrating one embodiment of the present invention applied to a fixed wavelength transmitter in a WDM fiber-optic data bus network operating with multiple wavelengths that is comprised of multiple Network Interface Units (NIU).

DETAILED DESCRIPTION OF THE INVENTION

In accordance with the invention disclosed herein, channel capacity of fiber-optical communication networks in a conventional Wavelength Division Multiplexing (WDM) network system can be significantly increased depending on the levels of polarization modulation. For a typical WDM system using a plurality of signal sources transmitting to a plurality of receivers at a plurality of different wavelengths, only the number of communication channels equal to the number of wavelength channels are available for data transmission. The present invention significantly increases the plurality of channels by a factor equal to the time division multiplex channels. This is achieved without requiring additional sets of laser sources.

One embodiment of the invention illustrated in Figure 1A shows a system with direct data modulation on optical sources. The system of Figure 1A has one set of network optical sources 12_1, 12_2 through 12_N where the 1-N represent N network optical sources. Each source 12_1, 12_2 through 12_N is driven by a temporal path consisting of Time Division Multiplexed (TDM) data from transmitter data processors 10_1 through 10_N. Each transmitter data processor 10_1, 10_2, 10_N multiplexes a plurality of input channels of data represented by L into a time division multiplexed data stream of temporal and spatial data.

The output spatial data path of transmitter data processors 10_1, 10_2, 10_N is directed to polarization modulators 14_1, 14_2, 14_N while temporal data is sent to optical sources 12_1, 12_2, 12_N for direct modulation. Each optical source 12_1, 12_2, 12_N is connected respectively to a polarization modulator 14_1, 14_2, 14_N. Polarization modulators 14_1, 14_2, 14_N produce optical symbols corresponding to various polarization states. For example, with a digital modulator implementation of polarization levels represented by M, mapping to 2^M distinct states, polarization modulators 14_1, 14_2, 14_N generate one optical pulse at the specific state of polarization per M input pulses from the spatial path. The same optical pulse carries the temporal modulated signal originated from the optical source. The output of each polarization modulator 14_1, 14_2, 14_N is sent to a Wavelength Division Multiplexer (WDM) 16 before being transmitted over transmission optical fiber 18.

Optical fiber 18 terminates and is connected to wavelength division demultiplexer 20. Each wavelength output of demultiplexer 20 is connected to a polarization demodulator 22_1, 22_2, 22_N. This is followed by direct photo-detection 24_1, 24_2 through 24_N and receiver data processing 26_1, 26_2, 26_N. Receiver data processors 26_1, 26_2, 26_N demultiplex the received TDM data from the received spatial and temporal data channels into a

plurality of output data channels represented by L.

A typical transmitter data processor 10 is illustrated in Figure 4A. Transmitter data processor 10 multiplexes input channels of data represented by L into time division multiplex data stream of temporal and spatial data by input/output (I/O) control time multiplex switch 28. The output of the transmitter data processors are then sent to the source or polarization modulator as described previously. The transmitter data processor performs the function of multiplexing multiple input channels of data into a time division multiplexed data stream of temporal and spatial data. The input and output sampling is controlled by the TDM I/O switch.

The mapping operation of a M-level polarization modulator from digital data to polarization symbols in a Poincare shpere using Stokes parameters is illustrated in Figure 5A while the implementation is illustrated in Figure 5B.

The implementation scheme of such a modulator 14 is shown in the block diagram of Figure 5B. Polarization modulator 14 is comprised of an optical input port connected to a polarization beam splitter 31 that produces two outputs with orthogonal polarization states. One such output will be rotated by polarization rotator 33 in its polarization angle while the other is phase modulated by the input data in phase modulator

35. After they transverse through directional coupler 37, the polarization angle is rotated back by polarization rotator 39 and recombined with another phase modulated signal from the input data by phase modulator 41, polarization processor 45, and polarization beamsplitter 43.

Polarization demodulator 22 is illustrated in Figure 5C. Polarization demodulator 22 is comprised of a Stokes parameter estimator 30, a control loop comprised of a track and hold circuit 32, analog to digital convertor 34, a filter 36, and digital to analog convertor 38, and decision logic block 40. The optical network system illustrated in Figure 1A operates with a plurality of wavelengths represented by N and polarization modulation levels per wavelength represented by M. In this present invention, the throughput has been increased by M times while the total number of channels has increased up to NxL where L is the number of TDM channels. The representations by N, M, and L are purely arbitrary and can be chosen to maximize a capacity meeting specific network requirements.

A variation of the system illustrated in Figure 1A in which like reference numbers indicate like parts throughout is illustrated in Figure 1B. In this embodiment rather than a simple transmission optical fiber 18 without signal amplification, optical amplifiers 42 are added to extend

transmission distance of optical fiber 18 for long-haul applications.

Another variation of the system and circuit illustrated in Figure 1A is shown in the schematic block diagram of Figure 1C where like reference numbers indicate like parts throughout. In this case, there are multiple sets of the circuits shown in Figure 1C to perform the multiplexing, modulation, demultiplexing and demodulation. However in this case, rather than using a single fiber-optic cable 18 as illustrated in Figure 1A having wavelength routing without reuse, an optical wavelength cross-connect is inserted in optical fiber transmission lines 18_1 through 18_N to reuse each wavelength a number of times equivalent to N for connecting various transmitters and receivers. For example, a first user I can use one of the L channels of wavelength λ1 to establish a link with a user II, while simultaneously user V can reuse the same wavelength (λ1) and channel to communicate with user VI. Compared to a typical WDM fiber-optic network system operating with multiple wavelengths without reuse represented by N, the total number of channels in this unique system is increased to (N^2xL), where L is the number of TDM channels.

Another embodiment of the invention is illustrated in Figure 2A in which like reference numbers identify like parts

throughout. In this embodiment, optical sources 12_1, 12_2, 12_N are not directly modulated. In this embodiment, the optical output signal from sources 12_1, 12_2, 12_N are spatial modulated in polarization and temporally modulated in amplitude, phase, and/or frequency by space-time modulators 14_1, 14_2, 14_N driven by transmitter data processors 10_1, 10_2, 10_N. In most applications, an indirect amplitude or indirect phase modulation is desirable to preserve the stability of optical sources 12_1, 12_2, 12_N. Polarization modulators 14_1, 14_2, 14_N may be implemented by Electro-Optical Modulators (EOM) or Electro-Absorptive Modulators (EAM). The output of each modulator 14_1, 14_2, 14_N is sent to Wavelength Division Multiplexer (WDM) 16 before being transmitted by optical fiber 18.

Optical fiber 18 terminates and is connected to wavelength division demultiplexer (WDM) 20. Each wavelength output of wavelength division demultiplexer is connected to a polarization demodulator 22_1, 22_2, 22_N. This is followed by coherent optical demodulation in photo-detectors 24_1, 24_2, 24_N and receiver data processors 26_1 26_2, 26_N. Photo-detectors 24_1, 24_2 through 24_N that provide the coherent optical demodulation can be implemented by a local optical source using homodyne or heterodyne demodulation techniques.

A variation of this system of Figure 2A is illustrated in

Figure 2B in which like reference numbers indicate like parts throughout. In this embodiment, rather than a simple transmission optical fiber 18 without signal amplification, optical amplifiers 42 are added to extend transmission distance of the fiber for long-haul applications.

A variation of the system of Figure 2A is illustrated in Figure 2C in which like reference numbers indicate like parts throughout. The system illustrated in Figure 2C comprises multiple sets of data processors and subsequent circuits of which can be represented by 1 through N. In this variation rather than wavelength routing without use, an optical wavelength cross-connect 44 is inserted in fiber-optic transmission lines 18_1 through 18_N to reuse each wavelength multiple times represented by N for connecting various transmitters and receivers. Thus, cross-connect will be an NxN wavelength cross-connect.

For example, a first user I can use one of the L channels of wavelength λ1 to establish a link with a second user II, while simultaneously a fifth user V can reuse the same wavelength (λ1) and channel to communicate with a sixth user VI. Compared to a typical Wavelength Division Multiplexer (WDM) fiber-optic network system operating with multiple wavelengths of N without reuse, the total number of channels of this new

design is increased to (N^2xL), where L is the number of TDM channels.

An optical wavelength cross-connect of NxN for insertion in fiber-optic transmission lines 18_1 through 18_N to reuse each wavelength N times for connecting various transmitters and receivers is illustrated in Figure 3. Each fiber-optic transmission line 18_1 through 18_N feeds into wavelength demultiplexer 46_1 through 46_N. Each demultiplexer 46_1 through 46_N provides an output to each wavelength multiplexer 48_1 through 48_N directly and by cross connection. Each multiplexer 48_1 through 48_N provides an output to fiber-optic transmission line 18_1 through 18_N with multiple wavelength division multiplexed wavelengths represented by N per fiber.

The invention disclosed herein can also be applied to a conventional wavelength division multiplexing ring network as illustrated in Figure 6 wherein like reference numbers again indicate like parts throughout. Similar to the embodiment of Figure 1A, there is one set of multiple optical sources 12_1, 12_2, through 12_N which can be represented by N. Each source 12_1, 12_2, 12_N is directly modulated by transmitter data processor 10_1, 10_2, through 10_N. The output temporal data path of each transmitter data processor 10_1, 10_2, 10_N is directed to each optical source 12_1, 12_2, 12_N, respectively, while spatial data is

sent to polarization modulators 14_1, 14_2, through 14_N. Polarization modulators 14_1, 14_2, 14_N produce optical symbols corresponding to various polarization states. The output of each polarization modulator 14_1, 14_2, 14_N is sent to Wavelength Division Multiplexer (WDM) 16_1 before being transmitted over fiber-optics transmission line 18. The wavelength output of wavelength division multiplexer 16_1 is sent by fiber-optic transmission line 18 to wavelength division demultiplexer 20_1 and add/drop node 50_1 to subsequent WDM 16_2 and multiple add/drop nodes through 50_N by a series of multiplexers 16_1 through 16_N and demultiplexers 20_1 through 20_N. Each add/drop node 50_1 through 50_N operates in a specific wavelength with L TDM Channels.

The specific wavelength outputs of wavelength division demultiplexers 20_1, 20_2, through 20_N (WDM) are connected to polarization demodulators 22_1, 22_2, through 22_N. They are followed by photo-detectors 24_1, 24_2, through 24_N for direct photo-detection and then received by receiver data processors 26_1, 26_2, through 26_N. Receiver data processors 26_1, 26_2, through 26_N demultiplex the received TDM data from the received spatial and temporal data channels into multiple output data channels L.

The combined signals in this TDM/PM/WDM ring contains multiple wavelengths represented by N, polarization levels

represented by M and TDM channels per wavelength represented by L. Each add/drop node 50_1 through 50_N contains a receiver transmitter pair 52_1 through 52_N and 54_1 through 54_N respectively. Each receiver 52_1 through 52_N is capable of polarization demodulation, direct photo-detection and received data processing of multiple output data channels L. Transmitters 54_1 through 54_N reverse the operation by time multiplexing multiple input data channels L, direct modulation onto optical sources followed by polarization modulation.

Wavelength division demultiplexer 20_1 extracts a signal at one wavelength and transmits a signal back through wavelength division multiplexer 16_1 at the same wavelength. The same operation is repeated on the next and subsequent add/drop nodes through 50_N on optical fibers 18_1 through 18_N until it reaches the end of the ring. The access into and egress out of the ring network is under computer control. If any receiver/transmitter unit 52_1, 52_N, 54_1, 54_N wishes to transmit signals, its transmitter sends data through the TDM channel. These optical signals pass through WDM multiplexers 16_1 through 16_N and circulate around the ring. Hence, in this embodiment, the number of network users at each add/drop nodes 50_1, 50_N increases a factor of L.

A conventional WDM fiber-optics star network of multiple

wavelengths represented by N consists of a star coupler connected to N nodes. Each node operates with one of the optical wavelengths N and has its own laser source transmitting light at the nodes particular wavelength to the star coupler which multiplexes the optical signals at various wavelengths. One of the N nodes is used as a central office of the network. The star coupler broadcasts any optical signals from one node to all the other nodes in the network. Each node also receives and demultiplexes broadcast signals from the star coupler to determine whether it has messages sent from other nodes.

An adaptation of the system disclosed herein is shown in still another embodiment of the present invention illustrated in Figure 7. In this embodiment star coupler 60 is connected to multiple nodes 62_1 through 62_N. Each star network has now increased its throughput by a multiple of M times, while the total number of channels has increased to NxL times. Network users in the present invention at each node 62_1 through 62_N, and 70 are allocated specific TDM channels in the transmitter/receiver data processor 72.

The temporal data path of transmitter/receiver data processor 72 is directed to optical source 74 in each node while spatial data is sent to polarization modulator 76 in each node. Polarization modulator 76 produces optical symbols corresponding

to various polarization states. The output of each polarization modulator 76 in each node at the particular wavelength is sent to star coupler 60 for distribution of the wavelength multiplexed signal to all other nodes 62_1 through 62_N. On the return path, the WDM signal is extracted from a wavelength division demultiplexer or through a wavelength tunable filter 78 and polarization demodulator 80. This is followed by detection in photo-detector 82 and processed by transmitter/receiver data processor 72. Transmitter/receiver data processor 72 in each node demultiplexes received TDM data and received spatial data.

A conventional WDM fiber-optic data bus network operating with multiple wavelengths of N is comprised of multiple Network Interface Units (NIU) communicating over an optical fiber. Each network interface unit by which a user communicates over the network, has multiple fixed wavelength optical transmitters and multiple receivers. Due to the hardware cost of installing multiple pairs of transmitter/receivers per interface network unit, each NIU in general only contains a few pairs of transmitter/receivers, such that multiple hops are required to relay messages from one user to another within the network. Network loading then becomes a problem during a high network utilization period. Furthermore, each NIU can only be shared by a small limited number of users due to few pairs of

transmitter/receivers are available.

In yet another embodiment of the present invention illustrated in Figure 8, each fixed wavelength transmitter 84 at NIU 85 is driven by a transmitter data processor. The temporal data path from the data processor is directed to the optical source while the spatial data is sent to the polarization modulator. The modulator produces symbols corresponding to various polarization states. The output of each polarization modulator at a specific wavelength circulates in data bus 88. A reverse operation is carried out by receiver 86. This is followed by direct photo-detection and received data processing. The receiver data processor demultiplexes the received TDM data and the received spatial data with multiple additional TDM channels of L. The same data bus 88 can now support L times more users without installing more transmitter/receiver pairs.

Thus there has been disclosed a unique system for increasing the capacity of fiber-optical communication networks by a system of time division multiplexing, polarization modulation, and wavelength division multiplexing. The space-time modulation provides large capacity expansion by utilizing three-dimensional spatial field. This increase in channel capacity can be achieved by a combination of Time Division Multiplexing (TDM), Polarization Modulation (PM), and

Wavelength Division Multiplexing (WDM) technology. By maintaining independence between spatial modulation, time and wavelength division multiplexing, channels derived from wavelengths in time slots can be separately assigned. The resulting degrees of freedom increase throughput and add flexibility in supporting multiple users in a large variety of optical network configuration and services.

This invention is not to be limited by the embodiment shown in the drawings and described in the description which is given by way of example and not of limitation, but only in accordance with the scope of the appended claims.